A CUSTOMER PERSPECTIVE ON THE EVOLUTION OF NUMERICAL WEATHER PREDICTION AS APPLIED TO NAVAL OPERATIONS - THE REAL STORY

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1. INTRODUCTION

Although the earliest operational use of NWP products dates back to the mid 1950s, it took many years for the models to reach sufficient skill to be used routinely without significant forecaster modification. Further, there was the technical problem of disseminating the NWP products to the forecast offices in the first place, to say nothing of the difficulty in getting such products to ships at sea.

To effectively use NWP in the early days required the application of various synoptic techniques to enhance the value of the NWP products for use in real-time forecasting. Sometimes these techniques worked and sometimes they didn't. However, they were essential to overcome the computational limitations of first the barotropic models, and then the early baroclinic "PE" models which employed the "primitive equations". Using techniques such as those documented by George (1960), synoptic meteorologists over the years were generally able to outperform increasingly sophisticated NWP models, until the hemispheric PE models of the 1970s were replaced by global finite difference and spectral models in the 1980s. These improvements and added complexities of global NWP models were made possible by increasingly powerful supercomputers and decreasingly expensive computational costs. This resulted in an eventual shift in forecaster culture from one of applying synoptic tools for the creation of a forecast to one of interpreting and disseminating the model output. This was a big change from simply using the models as just another tool toward achievement of the final forecast. Today, with the creation of automatically generated digital forecasts, the culture is changing further in the direction of forecast presentation techniques and away from the direction of experienced forecasting.

2. NAVY REQUIREMENTS FOR NWP

Aside from the obvious need for a better forecast to support all phases of Naval operations and infrastructure protection, the Navy had (and still has) unique requirements for skillful NWP, especially for extended time periods. Ship transits across expansive oceans can take two weeks or longer, and optimum track routing is required to save transit time and fuel costs while avoiding weather damage. There are similar requirements for aircraft routing. Additionally, as battle plans and related weather impacts move from the planning stage (climatology) to execution (today's forecast), they pass through an intermediate stage where decisions must be made based on likely weather and ocean conditions.

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This creates a need for viable mid-to-long range forecasts from seven to 30 days in length, techniques that even today show only limited skill. Until the advent of global NWP and operational climate models in recent years, these techniques were limited to weather typing schemes such as those developed at the California Institute of Technology in the 1930s, and to various synoptic climatology and related analog techniques.

3. SYNOPTIC TOOLS TO IMPROVE THE UTILIZATION OF EARLY NWP

Most early NWP techniques used hemispheric or partial hemispheric barotropic models with limited integration between upper air and surface, minimal coupling between air and sea (winds, heat flux, etc.), and little or no coupling between the tropics and temperate zones. The resultant forecast products were marginal at best, and had difficulty accurately reflecting synoptic features, with little synoptic skill beyond two days. As a result, synoptic techniques were developed to exploit the more skillful early NWP forecasts of large scale features; the results could then be applied to Navy forecast problems.

3.1 *Scale and Pattern Decomposition*

In order to better identify and more objectively define such phenomena in the total synoptic flow as vorticity maxima, long wave positions, and blocking patterns, a numerical technique was developed to separate any overall hemispheric synoptic pattern into its components of scale (Holl, 1963). This technique, applicable to any continuous height field (Z), objectively breaks down the total flow into its large and small scale components through the use of a successively applied mathematical smoother. The resultant parameters are the large (SL) and small (SD) scale disturbance fields, along with a thermally-driven planetary vortex (SV). This vortex is a combined measure of zonal wind and eccentricity. With the SV removed from the total flow, the remaining large and small scale features can thus be objectively identified. The SV and the SL combined yield the "residual field" (SR), which at 500 hPa essentially yields the hemispheric long-wave pattern. In equation form,

$$Z = SV + SL + SD;$$
$$Z = SR + SD; \text{ and}$$
$$SR = SV + SL$$

Synoptic rules could then be developed and applied to these features which would make up for some of the deficiencies of early day NWP. For example, pattern separation allowed one to objectively determine:

* long wave patterns and their expected progression or regression (from the SR),
* the position and strength of large scale blocking highs (from the SL),
* the relative energy associated with large scale disturbances and the related likelihood for cyclogenesis and subsequent development (from SL and SD components),
* the timing of cyclogenesis by following small scale disturbances (SD) through the base of long-wave troughs (SR).

This technique was instrumental in the application of NWP to operational forecast problems from the late 1960s into the late 1980s, by which time increasingly skillful global models rendered the synoptic techniques less necessary.

3.2 *Use of Analog Techniques*

During the Vietnam war, a requirement surfaced in the late 1960s for a 30-day forecast covering Southeast Asia.

The (then) Fleet Numerical Weather Central (today's Fleet Numerical Meteorology and Oceanography Center, or FNMOC) was tasked to address the problem scientifically. To respond to this requirement, an analog forecast technique already under development (Wolff and Thormeyer, 1969; McConathy and Thormeyer, 1974) was applied to the problem. This technique searched a continuous data base of historical 500 hPa and surface pressure charts dating back to 1946 for analogs by searching for matching large scale patterns as described above. Since individual analogs seldom correlated with existing patterns with coefficients any greater than 0.7 to 0.8, it was hard to pick the best analog either objectively or subjectively with the resultant forecast showing any degree of skill. However, it was determined that by combining the ten best analogs on any given day into an average "composite" forecast, the resultant skill was always greater than that of any of the individual analogs making up the composite (Hanna, 1971). Using the composite analogs, skill over persistence and climatology could then be shown out to at least eight days. Indeed, this averaging technique was very much like today's NWP "ensemble" techniques, with similar skill improvements resulting from combining individual forecasts into an average. Over the years, the Navy's analog forecasts were used for military problems as diverse as ocean wide four-week storm track forecasts in the Pacific Ocean, and energy consumption planning forecasts for the eastern seaboard of the United States. By the late 1980s, NWP had matured to the point where, with global spectral models and subsequent techniques, the dynamic forecasts outperformed the synoptic ones, and the analogs faded away in deference to the up-and-coming ensembles for the longer range problem.

4. DELIVERING NWP PRODUCTS TO NAVY FIELD OFFICES AND SHIPS

In the early days of NWP, transmission of final products to on-scene users (such as ships at sea) was limited to manually-operated facsimile broadcasts. However, these often did not reach the intended customer due to communications inadequacies (equipment, reception, bandwidth, etc.). As a result, the Navy embarked on a series of increasingly sophisticated product dissemination and display capabilities which were developed at and deployed from FNMOC.

4.1 *The Naval Environmental Data Network (NEDN)*

In July 1960, a (then) high speed communications line (1200 baud) was established between FNMOC and the Pacific Missile Range at Point Mugu, California. This line was designated as the first phase of the Naval Environmental Data Network, or NEDN. Once techniques were developed and peripheral equipment built or acquired (e.g., the CalComp Plotter), routine transmission of numerical weather and ocean products between the originator and a selected customer was demonstrated. In August 1963, the first NEDN link to an overseas site was established to the (then) Fleet Weather Central (FWC) at Pearl Harbor, HI, with the other Fleet Weather Centrals worldwide (now known as "regional centers") coming on line by the mid 1960s. These other sites were at Norfolk, VA, Suitland, MD, Rota, Spain, and Guam, Marianas Islands. By today's standards, such limited bandwidth would have been untenable, even with NEDN speeds reaching 9600 baud by 1979. As a result, major data compression and extraction routines were developed to "compact" all products before being transmitted from FNMOC, with "re-expansion" software at the user end.

The more vexing problem was converting a seemingly endless stream of digital bits into displayable products at the user sites. To this end, some combination of second-generation Control Data Corporation (CDC) 3200, 8090 and 160A computers were acquired for all the major sites listed above. By 1967, the NWP models were run on a third-generation CDC 6500 computer at FNMOC, compacted in-house and then transmitted as gridded products using CDC second-generation computers across the NEDN to the FWCs. Once received, these products were "expanded" (uncompacted) on the CDC 160A or 8090 and created into a display using first-generation computer plotting software on a CDC 3100. The output from the CDC 3100 was in the form of a seven-track digital tape, which was then mounted to specially designed peripheral equipment which drove a mechanical device known as a "CalComp Plotter". Varian electrostatic plotters gradually replaced the pen-driven CalComp plotters in the early 1970s, a technological advance which permitted far more flexibility in tailored chart production.

Next there was the issue of transmitting computer-generated products to fleet users, subject to all the communications constraints outlined above. In the late 1960s, these NWP products were manually "blown up" onto bigger hand-traced charts at the FWCs which covered their specific geographical areas of interest. The resulting charts were then modified manually by forecasters in-house who applied synoptic techniques to the numerical products. These products were then manually transmitted at scheduled times over an analog facsimile broadcast using equipment such as flat-bed scanners.

In the early 1970s, computer software evolved at the various FWCs to better automate the entire receipt-to-delivery process using the CDC equipment. Unfortunately much of this software was developed independently at each site, and was thus incompatible with similar computer systems at the other sites. Eventually, a standard set of software evolved in the mid 1970s, mostly generated by the team at FWC Pearl Harbor. A semi-automated facsimile capability was developed which permitted charts to be transmitted using a CDC 160A. The only manual intervention was the occasional mounting of magnetic tapes, each of which contained several products.

4.2 *The Naval Environmental Display Station (NEDS)*

With the Vietnam War ending and Defense budgets being reduced, the next challenge in disseminating NWP products was particularly daunting. The second-generation CDC equipment was becoming obsolete and hard to maintain, and replacing the hardware and software at the FWCs would have been prohibitively expensive. As a result, a decision was made to centralize all NWP chart production at FNMOC, and to develop a display capability for use at the FWCs which could also automatically drive a facsimile broadcast. Thus was born the Naval Environmental Display Station, or NEDS (Thormeyer, 1978). The NEDS served as one of the first operational interactive information processing systems, and as such was the first step toward an eventual "paperless" weather office. Minicomputer-based, it had both an alphanumeric and a graphic monitor, each with a keyboard. The alphanumeric monitor displayed textual reports and other information, including lists of available charts. It was also used for the creation of tailored forecasts which could then be transmitted to the end user, and for the building of facsimile schedules. The graphics monitor could display up to ten graphic overlays at one time including satellite imagery, and had an animated looping capability as well. Thus, one could review NWP products on the graphics monitor while generating a tailored forecast on the alphanumeric monitor. A "graph pen" (a precursor to today's mouse or trackball) permitted annotation of fronts, warning areas, etc. on charts for subsequent facsimile broadcast. Another innovation was the ability to exchange text messages between FWCs using the NEDS. This capability was one of the earliest "e-mail" systems in operational use.

The NEDS was phased in, overlapping the CDC equipment at the regional centers from 1977 to 1981. The last NEDS unit was finally retired in 1994 as technology evolved and PC systems came on-line. During this 17 year stretch, NEDS was the primary means of viewing and manipulating weather and ocean data at the regional centers, and served to standardize chart production and forecast generation procedures throughout the NEDN.

4.3 *The Navy Oceanographic Data Distribution System (NODDS)*

In spite of the success of the NEDS, the problem of getting Navy NWP products reliably to outlying sites other than the regional centers, and particularly to ships, still had not been solved. Navy NWP products were first displayable on special computer terminals other than NEDS in the late 1970s and on PCs by the mid 1980s at selected sites, but the system was limited and cumbersome. In 1990, a true PC-based system was developed - the Navy Oceanographic Data Distribution System, or NODDS (Thormeyer, et. al., 1995). Using a query-response approach, the user's PC-based NODDS software would generate a request for selected products which would then be created on FNMOC mainframes, and then returned to the user PC formatted as a compacted alphanumeric data stream. The NODDS software on the user's PC would then re-create the charts for display on the PC monitor. Over time, NODDS developed most of the same capabilities as NEDS; the difference being that anyone with a NODDS account, a PC, and a telephone connection could download and display FNMOC NWP products from anywhere in the world. NODDS account holders came from all the military services, and from numerous civil sector organizations as well. It was the first system to make FNMOC's NWP products routinely available to operational forecasters outside of the Navy.

4.4 *Web-based Data Display*

The Internet and World Wide Web changed everything in the world of meteorology and oceanography (METOC) product display, and a whole new set of display systems evolved. They include:

- The Joint METOC Viewer (JMV): By the mid 1990s, the more sophisticated Web-based JMV "thick client" software began replacing NODDS as the primary means of displaying Navy NWP products on PCs (Garthner, et. al., 1999). JMV remains in use today.

- WxMAP: In the late 1990s, one of the first net-centric systems for NWP chat display became operational at FNMOC. Called "WxMAP", one needed only a PC, a browser, and an Internet connection to access a selection of pre-defined charts. The system remains operational today.

- MyWxmap: This new system is presently replacing WxMAP. MyWxmap was developed as a true "Web Services" application using Beowulf clustering technology for central site chart production (Ravid and Lowder, 2000; Thormeyer and Ravid, 2003). First operational in April 2003, MyWxmap permits the user to create charts over customer-selected geographical areas, choose from a larger portfolio of available products, and perform model comparisons between NCEP and FNMOC product output. The chart display is more visually appealing; further, the system takes advantage of standard Web browser capabilities and functionality which were unavailable in previous systems. FNMOC NWP products are available to the general public through MyWxmap at www.fnmoc.navy.mil.

4.5 *Shipboard Support*

Despite technical progress in the dissemination of NWP products to a globally dispersed customer base, shipboard receipt of such products remained very limited until the advent of widespread Internet availability in the late 1990s. Before that time, fax broadcasts, when they could even be received, were limited to four charts per hour. As a result, shipboard meteorologists often resorted to foreign meteorological facsimile broadcasts, or to sets of NWP grid point values transmitted in an alphanumeric format from FNMOC which could then be hand-plotted on a blank chart and hand-analyzed. At times, "single station forecasting" or "mariner's eye" were the primary tools of the shipboard meteorologist. Today, however, the routine availability of NWP products and satellite imagery via secure Internet, at orders-of-magnitude greater bandwidth than that available on the early NEDN, is taken for granted by shipboard meteorologists. This recently acquired shipboard ability to select from a large volume of NWP products from various sources using high-speed communications in order to produce a forecast is truly the envy of those who served before.

5. SUMMARY

While NWP was a key scientific breakthrough in improving weather and ocean forecasts, the advent of the commercially available Internet was the technology which finally, after decades of frustration, allowed for the dissemination of NWP products to the users who needed them the most. As both the science of NWP and the technology of communications evolved, the Navy METOC officer also evolved from an expert synoptician to an expert interpreter and communicator of NWP information.

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